APPENDIX C. RADIATION AND HUMAN HEALTH

C.1 WHAT IS RADIATION?

Radiation is the emission and propagation of energy through space or through a material in the form of waves or bundles of energy called photons, or in the form of high-energy subatomic particles. Radiation generally results from atomic or subatomic processes that occur naturally. The most common kind of radiation is electromagnetic radiation, which is transmitted as photons. Electromagnetic radiation is emitted over a range of wavelengths and energies. We are most commonly aware of visible light, which is part of the spectrum of electromagnetic radiation. Radiation of longer wavelengths and lower energy includes infrared radiation, which heats material when the material and the radiation interact, and radio waves. Electromagnetic radiation of shorter wavelengths and higher energy (which are more penetrating) includes ultraviolet radiation (which causes sunburn), X-rays, and gamma radiation.

Ionizing radiation is radiation that has sufficient energy to displace electrons from atoms or molecules to create ions. It can be electromagnetic (for example, X-rays or gamma radiation) or subatomic particles (for example, alpha and beta radiation). The ions have the ability to interact with other atoms or molecules; in biological systems, this interaction can cause damage in the tissue or organism.

Radioactivity is the property or characteristic of an unstable atom to undergo spontaneous transformation (to disintegrate or decay) with the emission of energy as radiation. Usually the emitted radiation is ionizing radiation. The result of the process, called radioactive decay, is the transformation of an unstable atom (a radionuclide) into a different atom, accompanied by the release of energy (as radiation) as the atom reaches a more stable, lower energy configuration.

Radioactive decay produces three main types of ionizing radiation—alpha particles, beta particles, and gamma or X-rays—but our senses cannot detect them. These types of ionizing radiation can have different characteristics and levels of energy and, thus, varying abilities to penetrate and interact with atoms in the human body. Because each type has different characteristics, each requires different amounts of material to stop (shield) the radiation. Alpha particles are the least penetrating and can be stopped by a thin layer of material such as a single sheet of paper. However, if radioactive atoms (radionuclides) emit alpha particles in the body when they decay, there is a concentrated deposition of energy near the point where the radioactive decay occurs. Shielding for beta particles requires thicker layers of material such as several reams of paper or several inches of wood or water. Shielding from gamma rays, which are highly penetrating, requires very thick material such as several inches to several feet of heavy material (for example, concrete or lead). Deposition of the energy by gamma rays is dispersed across the body in contrast to the local energy deposition by an alpha particle. In fact, some gamma radiation will pass through the body without interacting with it.

Radiation that originates outside of an individual's body is called external or direct radiation. Such radiation can come from an X-ray machine or from radioactive materials (materials or substances that contain radionuclides) such as radioactive waste or radionuclides in soil. Internal radiation originates inside a person's body following intake of radioactive material or radionuclides through ingestion or inhalation. Once a radioactive material is in the body, its fate is determined by its chemical behavior and how it is metabolized. If the material is soluble, it might be dissolved in bodily fluids and transported to and deposited in various body organs; if it is insoluble, it might move rapidly through the gastrointestinal tract or be deposited in the lungs.

C.2 RADIATION DOSE

Exposure to ionizing radiation is expressed in terms of absorbed dose, which is the amount of energy imparted to matter per unit mass. Often simply called dose, it is a fundamental concept in measuring and quantifying the effects of exposure to radiation. The unit of absorbed dose is the rad.

The different types of radiation mentioned above have different effects in damaging the cells of biological systems. Dose equivalent is a concept that considers the absorbed dose and the relative effectiveness of the type of ionizing radiation in damaging biological systems, using a radiation-specific quality factor. The unit of dose equivalent is the rem.

In quantifying the effects of radiation on humans, other concepts are also used. The concept of effective dose equivalent is used to quantify effects of radionuclides in the body. It involves estimating the susceptibility of the different tissue in the body to radiation to produce a tissue-specific weighting factor. The weighting factor is based on the susceptibility of that tissue to cancer. The sum of the products of each affected tissue's estimated dose equivalent multiplied by its specific weighting factor is the effective dose equivalent. The potential effects from a one-time ingestion or inhalation of radioactive material are calculated over a period of 50 years to account for radionuclides that have long half-lives and long residence time in the body. The result is called the committed effective dose equivalent. The unit of effective dose equivalent is also the rem. Total effective dose equivalent is the sum of the committed effective dose equivalent from radionuclides in the body plus the dose equivalent from radiation sources external to the body (also in rem). All estimates of dose presented in this environmental assessment (EA), unless specifically noted as something else, are total effective dose equivalents, which are quantified in terms of rem or millirem (which is one one-thousandth of a rem).

More detailed information on the concepts of radiation dose and dose equivalent are presented in publications of the National Council on Radiation Protection and Measurements (NCRP 1993) and the International Commission on Radiological Protection (ICRP 1991).

The factors used to convert estimates of radionuclide intake (by inhalation or ingestion) to dose are called dose conversion factors. The International Commission on Radiological Protection and federal agencies such as the U.S. Environmental Protection Agency (EPA) publish these factors (Eckerman and Ryman 1993; Eckerman et al. 1988). They are based on original recommendations of the International Commission on Radiological Protection (ICRP 1977).

The radiation dose to an individual or to a group of people can be expressed as the total dose received or as a dose rate, which is dose per unit time (usually an hour or a year). Collective dose is the total dose to an exposed population. Person-rem is the unit of collective dose. Collective dose is calculated by multiplying the individual dose by the number of individuals in a population. For example, if 100 workers each received 0.1 rem, the collective dose would be 10 person-rem (100 × 0.1 rem).

Exposures to radiation or radionuclides are often characterized as being acute or chronic. Acute exposures occur over a short period of time, typically 24 hours or less. Chronic exposures occur over longer times (months to years); they are usually assumed to be continuous over a period, even though the dose rate might vary. For a given dose of radiation, chronic radiation exposure is usually less harmful than acute exposure because the dose rate (dose per unit time, such as rem per hour) is lower, providing more opportunity for the body to repair damaged cells.

On average, members of the public nationwide are exposed to approximately 300 millirem per year from natural sources (NCRP 1987). The largest natural sources are radon-222 and its radioactive decay products in homes and buildings, which contribute about 200 millirem per year. Additional natural sources include radioactive material in the Earth (primarily the uranium and thorium decay series, and potassium-40) and cosmic rays from space filtered through the atmosphere. With respect to exposures resulting from human activities, the combined doses from weapons testing fallout, consumer and industrial products, and air travel (cosmic radiation) account for the remaining approximate 3 percent of the total annual dose. Nuclear fuel cycle facilities contribute less than 0.1 percent (0.05 millirem per year) of the total dose.

C.3 POTENTIAL TO INCUR CANCER (LINEAR-NO-THRESHOLD MODEL)

Cancer is the principal potential risk to human health from exposure to low or chronic levels of radiation. When radiation interacts with tissue, it deposits a small amount of energy. The deposited energy—the dose – causes the molecules of tissue to undergo transformations. These transformations, in turn, create changes in cell function. If the dose is very high, these changes disrupt the function of the cells, tissues, and organism to such an extent that severe illness ("acute radiation syndrome") is induced. At low doses, these changes generally do not create significant effects in the cells and tissues as the body has a number of corrective defense systems that remove the damage or eliminate the damaged cell. Nevertheless, the possibility exists that these induced changes could escape the protective functions and result in the induction of cancer.

This EA expresses radiological health impacts as the incremental changes in the number of expected fatal cancers (latent cancer fatalities) for populations and as the incremental increases in lifetime probabilities of contracting a fatal cancer for an individual. The estimates are based on the dose received and on dose-to-health-effect conversion factors recommended by the International Commission on Radiological Protection (ICRP 1991). This is called the Linear-No-Threshold model of radiation risk. The Commission estimated that, for the general population, a collective dose of 1 person-rem will yield 0.0005 excess latent cancer fatality. For radiation workers, a collective dose of 1 person-rem will yield an estimated 0.0004 excess latent cancer fatality. The higher risk factor for the general population is primarily due to the inclusion of children in the population group, while the radiation worker population includes only people older than 18.

For example, a population would have to be exposed to a radiation dose of 2,000 person-rem for there to be 1 excess latent cancer fatality:

0.0005 latent cancer fatalities/person-rem × 2,000 person-rem = 1 latent cancer fatality

If a member of the public were exposed to a radiation dose of 15 millirem per year for 40 years,[1] the lifetime probability of a latent cancer fatality would be about 0.0003:

0.0005 latent cancer fatalities/person-rem × 15 millirem/year × 40 years × 1 rem/1,000 millirem = 0.0003 probability of a latent cancer fatality

If a member of the public were exposed to a radiation dose of 0.05 millirem per year for 40 years, the lifetime probability of a latent cancer fatality would be about 1×10^{-6}:

[1] The non-isotope specific fatal cancer risk factor in ICRP 60 (1991) is 0.0005 fatality per person-rem or an individual fatal cancer risk of 0.0005 per rem. EPA uses the non-isotope specific dose risk correlation of 15 millirem/year to an individual cancer risk of 3×10^{-4} (*see* OSWER 9200.4-18). Exposure period = (3×10^{-4} x 1.000 millirem/rem) / (15 millirem/y x 0.0005 per rem) = 40 years. Thus, a 40-year exposure period was used in order to make 0.0005 and 3×10^{-4} consistent.

0.0005 latent cancer fatalities/person-rem $\times$ 0.05 millirem/year $\times$ 40 years $\times$ 1 rem/1,000 millirem = 1×10^{-6} probability of a latent cancer fatality

Other health effects such as nonfatal cancers and genetic effects can occur as a result of chronic exposure to radiation. Inclusion of the incidence of nonfatal cancers and severe genetic effects from radiation exposure increases the total detriment by 40 to 50 percent (Table C-1), compared to the change for latent cancer fatalities (ICRP 1991). As is the general practice for any U.S. Department of Energy (DOE) EA, estimates of the nonfatal cancers and severe genetic effects were not included in this EA.

Table C-1. Risk of Latent Cancer Fatalities and Other Health Effects from Exposure to Radiation

Population	Latent Cancer Fatality	Nonfatal Cancer	Genetic Effects	Total Detriment
Workers	0.0004	0.00008	0.00008	0.00056
General Population	0.0005	0.00010	0.00013	0.00073

Source: ICRP (1991)

The Linear-No-Threshold model postulates that there is a theoretical, non-zero risk at low doses of radiation, even at or below the levels of background radiation. Exposure to high levels of ionizing radiation can and does result in detrimental health effects including cancer; however, there is no scientific evidence to support the presence of any increase in cancer risk at levels below 10,000 millirem in addition to background radiation. Exposure from natural background radiation averages 300 millirem per year in the United States. Therefore, in a normal lifetime of 75 years, an individual should expect to be exposed to approximately 22,500 millirem. This background radiation comes from soil and rock, food, cosmic rays, and indoor radon.

The Linear-No-Threshold model is based on scientists' estimate of the cancer risk from high levels of radiation exposure based upon cancers observed in the survivors of the nuclear explosions in Hiroshima and Nagasaki. These survivors were exposed to hundreds of rem (or hundreds of thousands of millirem) instantaneous dose, plus subsequent long-term exposure from fallout. Based on these studies, scientists have estimated the cancer risk from radiation exposure at high doses and high dose rates to be approximately 0.05 per 100 rem. That is to say, if a person receives 100-rem exposure he/she has a 5 percent or 5-in-100 chance of developing a fatal cancer.

Thus, using the Linear-No-Threshold model, the hypothetical cancer risk due to 1 millirem would be 0.0000005 or 5 in 10 million. Using the Linear-No-Threshold model and a *40-year residence* (exposure) period, the hypothetical risk due to exposure to 15 millirem per year would be 3 in 10,000. The dose rate equivalent to a hypothetical cancer risk of 1-in-a-million would be 0.05 millirem per year.

Using the Linear-No-Threshold model, the hypothetical cancer risk from background radiation for a *75-year lifetime* would be 75 years x 300 millirem/year x 0.0000005 = 0.01 or 1 in 100. Using the Linear-No-Threshold model, the hypothetical cancer risk from radiation exposure from clean soil, containing naturally occurring radionuclides, would be would be 75 years x 30 millirem/year x 0.0000005 = 0.001 or 1 in 1,000.

It is important to understand that the Linear-No-Threshold model is a hypothetical statistical model, and that its use at low dose rates is extremely conservative. There is no scientific evidence that small variations in radiation exposure, much less than the variability in natural background radiation levels, result in any increase in cancer risks. The following scientific and government bodies support the concept of a threshold at about 5,000 to 10,000 millirem above background, below which there is no cancer risk from radiation exposure.

- The National Academy of Sciences states, "With few exceptions, however, [cancer] effects have been observed only at relatively high doses and high dose rates. Studies of populations, chronically exposed to low level radiation, such as those residing in regions of elevated natural background radiation [10 - 100 times average US levels], have not shown consistent or conclusive evidence of an associated increase in the risk of cancer." (National Academy of Sciences 1990).

- The Health Physics Society states, "The Health Physics Society recommends against quantitative estimation of health risk below an individual dose of 5,000 millirem in one year or a lifetime dose of 10,000 millirem in addition to background radiation. There is substantial and convincing evidence of health risks at high dose. Below 10,000 millirem (which include occupational and environmental exposures), risks of health effects are either too small to be observed or are non-existent." (Health Physics Society 2001).

- The General Accounting Office states, "According to a consensus of scientists, there is a lack of conclusive evidence of low level radiation effects below total exposures of about 5,000 to 10,000 millirem." (GAO 2000).

C.4 ISOTOPE-SPECIFIC RISK FACTORS

Throughout the EA, a dose of 15 millirem per year is correlated to a theoretical lifetime cancer fatality risk of 3×10^{-4}. Likewise, by simple rationing, a theoretical lifetime cancer fatality risk of 10^{-6} has been correlated to a dose of 0.05 millirem per year. This simple statistical correlation derives from the Linear-No-Threshold model relating whole-body dose and risk. It is used by regulatory agencies, including the EPA, to correlate dose and risk (*see,* for example, OSWER Memorandum 9200.4-18 [EPA 1997]).

In reality, the correlation is more complex and depends on many more factors, including radioisotope generating the dose, radiation type generating the dose, period over which dose is received, body organ receiving the dose, cancer type incurred, age at exposure, age at onset of cancer, lag time between these two times, and other lifestyle and environmental confounders such as smoking history.

C.5 REFERENCES

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